

Chronic Traumatic Encephalopathy as a Consequence of Repetitive Sports Head Injury: A Review

Michael A. Galgano, Robert Cantu, Lawrence S. Chin

1.

Corresponding author: Michael A. Galgano, mgalgano13@gmail.com

Abstract

Chronic traumatic encephalopathy (CTE) is a disabling condition seen most frequently in athletes involved in high-impact sports. Physical and emotional abnormalities begin to display themselves later on in an athlete's life. Routine neuroradiographic imaging generally does not show any significant findings; however, newer MRI-based techniques, such as DTI, fMRI, and MRS, have shown promise for earlier detection. Three stages of the clinical presentation of CTE have been described. CTE likely results from progressive neuronal loss. Once the cascades are started, the symptoms of CTE become progressive. Sport-specific preventive strategies and early detection in our athletes is of vital importance in the management of CTE.

Categories: Neurology, Physical Medicine & Rehabilitation, Neurosurgery

Keywords: chronic traumatic encephalopathy, mild traumatic brain injury, concussion, high-impact sports, athletics

Introduction And Background

Every year, 1.5 million Americans suffer traumatic brain injuries without loss of consciousness or hospitalization [1]. A large number of these injuries, often loosely termed "concussions", occur during sports. They account for 10% of all head and spinal cord injuries, and the Center for Disease Control attributed 207,830 emergency room visits per year between 2001 and 2005 to non-fatal sports-related head injuries [2]. A study of high school athletes found that all sports were at risk for concussions with boys' football being the highest at 63% of the total followed by wrestling (10%), soccer (6%), with the remainder in basketball, softball, baseball, field hockey, and volleyball [3-4]. A sport that poses a very high risk of chronic traumatic brain injury not seen in high school athletics is professional boxing. In a previous well-designed prevalence study conducted four decades ago, it was estimated that approximately 17% of retired professional boxers exhibit characteristics of chronic traumatic brain injury [5].

Concussion is generally defined as a mild injury to the brain caused by traumatic biomechanical forces without radiographic evidence of damage. It may be caused by a direct blow to the head or a force that leads to acceleration of the head without direct trauma. A concussion does not imply loss of consciousness and 90% of concussions due to sports present this way [6]. Concussions typically result in headaches, dizziness, confusion, disorientation, and blurred vision.

Although once thought to be benign, there is increasing evidence that a concussion or mild traumatic brain injury (mTBI) have more serious complications, particularly when they occur repeatedly. Sports-related chronic traumatic encephalopathy (CTE) manifests as a progressive worsening of cerebral neurological symptoms, initiated by and perhaps worsened by repetitive concussions and subconcussive injuries. While the precise incidence and prevalence of CTE is not known, recent epidemiological data have shown that 17% of the individuals with repetitive mTBI may develop CTE; however, the severity and the frequency of repetitive injury needed to cause CTE is still unknown [7-10].

Research regarding concussions in the youth population remains rather limited, despite an increasing number of reported individuals being treated in US emergency departments. According to a report from the Committee on Sports Concussions in Youth, individuals aged 19 and under seen in an emergency department for concussions and other non-fatal, sports and recreational-related TBI's, increased from 150,000 in 2001 to 250,000 in 2009 [11]. As a result of this increased awareness, there are new protective devices being advertised for young athletes, and some of these are sold under the premise that they may limit the concussion risk. However, there continues to be no solid scientific evidence supporting these devices. It is known that the youth population is rather resistant to reporting concussive events. This attitude unfortunately perpetuates further concussive events, since a history of concussions increases the risk of further concussions. Athletes, who return to play before their first concussive event is healed, place themselves at a significant risk for a second significant brain injury, and the adverse effects of the cumulative process.

Historical Background:

How to cite this article

Galgano M A, Cantu R, Chin L S. (December 10, 2014) Chronic Traumatic Encephalopathy as a Consequence of Repetitive Sports Head Injury: A Review. Cureus 6(12): e234. DOI 10.7759/cureus.234

Received 11/20/2014
Review began 11/27/2014
Review ended 12/09/2014
Published 12/10/2014

© Copyright 2014

Galgano et al. This is an open access article distributed under the terms of the Creative Commons Attribution License CC-BY 3.0., which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

In 1928, Martland introduced the term punch-drunk to describe neurological symptoms such as confusion, tremors, slowed speech and gait seen in boxers suffering from repeated blows to the head [11]. This came to be known as dementia pugilistica by Millsbaugh [12], and then Courville introduced the term psychopathic deterioration of pugilists [13]. The neuropathology of CTE was first described by Brandenburg, Hallevorden, and later Corsellis who found several characteristic areas of damage: septum pellucidum, adjacent periventricular gray, frontal and temporal lobes, substantia nigra, cerebellar scarring, and diffuse neuronal loss [7, 14-15]. Although originally described in boxers, CTE has since been found in other sports, including football, wrestling, and hockey as well as in individuals suffering repetitive brain trauma that were not athletes [7, 14]. It more recently has also been found in military blast victims.

Review

Clinical presentation

Patients with CTE present with headaches, dizziness, an unsteady gait, fatigue, and dysarthria. In addition they may have cognitive and psychosocial symptoms such as memory loss, attention deficit, difficulty in concentration, slow information processing, confusion, loss of judgment, irritability, emotional distress, and show an inability to stay employed. In severe cases there is a progressive slowing of movement, a propulsive gait, tremor, masked facies, deafness, dysarthria, dysphagia, ptosis and other ocular abnormalities [7]. Clinical deterioration in CTE typically occurs in three stages [7, 14]:

Stage 1 - affective disturbances and psychotic symptoms

Stage 2 - social instability, erratic behavior, memory loss, and initial symptoms and signs of Parkinsonism.

Stage 3 - general cognitive dysfunction, progression of dementia, speech and gait abnormalities, or full-blown Parkinsonism.

The initial symptoms are due to damage in the limbic system resulting in behavioral symptoms such as emotional lability, aggression and violence. Hippocampal as well as medial thalamus and entorhinal cortex involvement account for the memory disturbances. Disinhibition occurs as more frontal lobe involvement develops and degeneration in temporoparietal and occipital cortex results in visuospatial symptoms. Finally, in the late stages, degeneration of the substantia nigra causes Parkinsonian symptoms [7, 16-17].

The diagnosis of the CTE related to sports is based on a history of repetitive concussions, which may have been subclinical, evidence of disease progression, and the neurological exam. CT and MRI can be helpful for excluding other causes of neurological symptoms such as chronic subdural hematoma or brain tumor. Imaging may also identify nonspecific changes such as atrophy, encephalomalacia, and demyelination.

Notable Diagnoses in Athletes:

In no other sport has the diagnosis of CTE made more impact than in American football. In 2005, Omalu, et al. identified pathology consistent with CTE in a National Football League (NFL) player who had died of atherosclerotic heart disease 12 years after a long career in the NFL [18]. Interestingly, family members noticed that he had suffered from memory deficits and Parkinsonian symptoms.

More recent cases have resulted in greater media attention. Four years after competing in the Superbowl, NFL star Junior Seau committed suicide in 2012. This sparked significant awareness after the family of the NFL player decided to sue the National Football League. Most notably, 1987 NFL Man of the Year Award-winner Dave Duerson committed suicide in early 2011. The 50-year-old former Chicago Bears safety who died of a self-inflicted gunshot wound to the chest left a note asking that his brain be "given to the NFL's brain bank" at the Boston University Center for the Study of Traumatic Encephalopathy (BU CSTE). Through his work with the football players union, Duerson was aware of CTE and other cases of retired players who had suffered from CTE-like symptoms. For example, Mike Webster, Justin Strzelczyk, and Terry Long, all of the Pittsburgh Steelers, Andre Waters of the Philadelphia Eagles, Chris Henry of the Cincinnati Bengals, John Grimsley of the Houston Oilers, and Tom McHale of the Tampa Bay Buccaneers, all died after years of strange, erratic, and sometimes overly aggressive behavior.

Omalu, et al. reported a case of chronic traumatic encephalopathy in an American professional wrestler, Chris Benoit. He had sustained multiple blows to the head over his career. Initially, he presented with significant depression at the age of 36, and eventually committed a murder-suicide involving his wife and son a few years later. Autopsy later revealed randomly distributed NFT's and ghost tangles in the neocortex, subcortical ganglia, and brainstem nuclei. [19,20]

Ryan Freel was the first Major League Baseball player to be diagnosed with chronic traumatic encephalopathy. He died of a self-inflicted gunshot wound in December 2012. A report of Freel's condition was presented from the Boston University Center for the Study of Chronic Traumatic Encephalopathy and

Sports Legacy Institute. It stated that he suffered from stage II CTE when he died. Freel suffered multiple concussions during his playing career, and was hospitalized in 2007 after colliding with another player.

Other notable cases from BU CSTE included Owen Thomas, a 21-year-old football player at the University of Pennsylvania who committed suicide by hanging himself, and was subsequently diagnosed with CTE. With more than a million teenagers competing in football every year, it is clear that the risk of CTE looms as a potential public health disaster.

Pathological Findings:

Brain specimens with CTE show a reduction in weight, enlargement of the ventricular system especially lateral and third ventricle, thinning of corpus callosum, atrophy of cerebral hemispheres, mesial temporal lobes, thalamus, mammillary bodies, olfactory bulbs and brainstem, pallor in the substantia nigra and locus coeruleus, a cavum septum pellucidum, and scarring of the cerebellar tonsils.

Neuronal loss and gliosis are the most common microscopic findings in CTE and are usually associated with neurofibrillary degeneration especially in hippocampus, subiculum, entorhinal cortex, amygdala, subcallosal and insular cortex, frontal and temporal cortex, mamillary bodies, substantia nigra, locus coeruleus, nucleus accumbens, medial thalamus, pars compacta, and pars reticulata [7, 21–23]. The pathognomonic neuropathological sign of CTE is finding tau-immunoreactive neurofibrillary tangles with preferential involvement of superficial cortical layers, an irregular and patchy distribution in the frontal and temporal cortex, a propensity for sulcal depths, and a perivascular, periventricular and subpial distribution. Unlike Alzheimer's disease (AD), which shares a similar neuropathology, tau deposition in CTE is denser and preferentially found in neocortical layers II and III. Beta-amyloid deposition in CTE is also more sporadic compared to AD [7].

Pathophysiology:

Chronic traumatic encephalopathy likely results from progressive neuronal loss, but the exact mechanisms are unclear. CTE caused by repetitive mTBI continues to progress decades after the injuries have stopped indicating that once the cascades are initiated, they continue to execute their effects, and that, the longer the individual lives, the worse the symptoms [7, 16]. The severity threshold of the brain injury that can initiate these progressive chronic neurodegenerative changes, as well as the frequency are still unknown.

The patchy cortical distribution of NFTs suggests that their location is correlated with areas of direct mechanical trauma from blows to the side or top of the head. An ischemic basis of injury comes from the observation that tau deposition tends to be in the depths of cortical sulci [7]. The associated breakdown of the blood-brain barrier following brain injury with release of local neurotoxins potentially explains the perivascular clustering of NFTs [24]. Buee, et al. examined the microvasculature in patients with dementia pugilistica and found decreased microvasculature density and tortuosity, which corresponds to the laminar distribution of tau-positive NFTs [25]. In addition to tau, other protein inclusions may play an important role in CTE. The DNA binding protein TDP-43 along with tau has been observed in all of our brains with CTE and the brains and spinal cords of athletes presenting simultaneously with CTE and motor neuron disease suggesting a common link between CTE and sporadic amyotrophic lateral sclerosis. [26] While the exact function of TDP-43 is unknown, its overexpression causes neuronal degeneration and cell death in animal models [27]. One possible hypothesis is that mild traumatic brain injury causes axonal shear with cytoskeletal disruption.

As part of the injury response, TDP-43 is upregulated and binds to neurofilament mRNA in order to stabilize the transcript. Because this protein is prone to aggregation, pathological TDP-43 deposits form resulting in neurotoxicity and cell death.

Symptomatic Management:

Athletes engaging in high impact sports, whether it is at the professional, collegiate, or high school level, should be counseled on the importance of reporting symptoms as well as “occult” concussive events not visibly recognized by team trainers. If an individual is known to have sustained repetitive concussive or sub-concussive blows to the head over time, they should be referred to a specialty center such as a concussion clinic. Such clinics provide individuals with a multidisciplinary approach to their care, whereby psychiatry, neurology, and neurosurgery services can be provided as needed. It is important for ‘at-risk’ athletes to have surveillance for suicidal tendencies, access to behavioral / counseling services, and routine neurocognitive, neuropsychiatric, and functional capacity evaluations.

Prevention:

Because there are no known treatments for CTE, prevention of concussion and subconcussive blows is the only option. Prevention strategies must be sport-specific. For example, several risk factors for CTE in the

sport of boxing have been identified. Studies have shown that older boxers, those with long careers, poor performers, and individuals who have suffered several concussive blows are at the highest risk. These athletes should be identified and be required to go undergo a more extensive neurological evaluation. A more controversial but interesting aspect of prevention is genetic testing. Apo E4 is speculated to be a susceptibility gene in both football and boxing. The presence or absence of this gene may in fact be an important modifier of a particular athlete's overall risk of developing CTE [5].

An important part of prevention is the improved recognition of concussion on the playing field. It has been shown that suffering a first concussion increases the likelihood of a second concussion up to threefold. [28] Standardized concussion tools have been developed that assist physicians and trainers in this assessment. Concussion grading scales such as the Cantu system use loss of consciousness, post-traumatic amnesia length, and post-concussion signs and symptoms to determine severity.

Grade	Level of Consciousness
Grade 1 (mild)	No LOC*, PTA** <30 min, PCSS *** <24h
Grade 2 (moderate)	LOC < 1 min or PTA ≥ 30 min <24 h or PCSS ≥ 24 h <7 d
Grade 3 (severe)	LOC ≥ 1 min or PTA ≥ 24 h or PCSS ≥ 7 d

TABLE 1: Cantu Evidence-Based Grading System for Concussion

*LOC-Loss of consciousness ** PTA – Post traumatic amnesia *** PCSS – Post-concussion signs and symptoms

There has been tremendous research and development in designing new helmets, but their effectiveness in preventing concussions has not been proven. Mouth guards can reduce dental injuries but also have little impact on preventing concussions. Padded goal-posts in soccer can help prevent more serious brain injuries in this sport. In addition, lighter waterproof balls can be considered to reduce the impact of the ball striking the head during heading. However, there is some concern that protective equipment results in more aggressive play and may paradoxically increase the incidence of injuries. [29]

Return to play (RTP) guidelines have been developed that will hopefully decrease the risk of catastrophic injuries such as second impact syndrome as well as CTE. The RTP guidelines are based on concussion severity and require that the athlete be symptom free at rest and exertion for at least one week before being considered ready to return.

Grade	1st Concussion	2nd Concussion	3rd Concussion
1	when asymptomatic, one week	in two weeks if asymptomatic	terminate season; may return next season if asymptomatic
2	when asymptomatic, one week	in one month if asymptomatic	terminate season; may return next season if asymptomatic
3	in one month if asymptomatic	terminate season; may return next season if asymptomatic	terminate season; may return next season if asymptomatic

TABLE 2: Cantu Return to Play Guidelines

Note: Asymptomatic athlete is free of symptoms for one week

When a second concussion is suffered, the time period that the athlete must wait varies from two to four weeks depending on concussion severity. After three concussions (two, if severe), the player should terminate. There has been tremendous research and development in designing new helmets, but their effectiveness in preventing concussions has not been proven. Mouth guards can reduce dental injuries but also have little impact on preventing concussions. Padded goal-posts in soccer can help prevent more serious brain injuries in this sport. In addition, lighter waterproof balls can be considered to reduce the impact of the ball striking the head during heading. However, there is some concern that protective equipment results in more aggressive play and may paradoxically increase the incidence of injuries [29].

Return to play (RTP) guidelines have been developed that will hopefully decrease the risk of catastrophic injuries, such as second impact syndrome as well as CTE. The RTP guidelines are based on concussion severity and require that the athlete be symptom-free at rest and exertion for at least one week before being considered ready to return (Table 2). The season and return the next year. Once RTP is initiated, a graduated approach to increasing physical activity is used. This involves starting with exercises and then progresses to more sport-specific activities followed by gradual return to contact activities. If symptoms return at any point, the athlete should return to the previous level of activity.

Future direction and research:

Advanced Imaging:

It is widely accepted that concussion results mainly in functional disturbances as opposed to gross structural damage [30]. In concussed athletes, routine neuroimaging findings are generally negative. However, more novel imaging techniques using MRI, such as diffusion tensor imaging (DTI) and functional MRI (fMRI), may result in earlier diagnosis of concussion. Concussive impacts on the brain often result from acceleration / deceleration forces. Biomechanical strain on white matter may in fact lead to alterations in brain metabolism and electrophysiology. In 1967, Peerless and Rewcastle specified “shear-strain injury, or “traumatic axonal injury. This particular type of injury to the axons is generally seen at the junction between the gray and white matter. The shearing that takes place at this junction from acceleration / deceleration forces targets this area of the brain because of the physical make-up of the two different tissue types at this junction. The gray and white matter differ with respect to their rigidity. One of the main properties contributing the tissue characteristics of white matter is the myelin sheath which surrounds the axons [31]. Hovda and colleagues have published recent results that indicate automated analysis of MRI scans can provide clinicians with information that may help in assessing patients with mTBI. Zhang et al. compared MRI with DTI in 49 professional boxers and found only nonspecific white matter changes on MRI, but diffusion anisotropy analysis revealed a decrease in the average diffusion constant and whole brain diffusion [28]. These changes may indicate an early response to concussion in athletes and could become a useful tool both for detecting early damage and monitoring long-term neurological deficits.

Diffusion tensor imaging (DTI) is an MRI-based imaging modality which provides information on the microstructural integrity of the brain white matter tracts. It does this by measurement of water molecule diffusion within white matter. Because DTI is sensitive to white matter tracts, it has the ability to give us radiographic information regarding their disruption [31]. Some studies have shown a correlation between fractional anisotropy, which is a measure of axonal integrity, and functional tests of post-concussive states, such as eye tracking [32]. DTI can also provide information in regards to grey matter integrity as well. Gliosis and necrosis found on a DTI scan of an athlete may in fact be an indicator of brain injury from repetitive concussions [33].

Functional magnetic resonance imaging (fMRI) is another imaging modality that has the ability to capture neuronal activation via activation changes in blood oxygen level dependent (BOLD). It is presumed that the neural substrates of a particular task are represented by changes in signal intensity. The changes in signal are due to changes in the state of oxygenation of hemoglobin in the specific areas of brain which are activated during these tasks. Studies related to fMRI have a focus on working memory, as this is what has been primarily examined in regards to this imaging technique. Some may conclude that sports-related concussions are primarily a disorder of frontal network functioning [33].

Magnetic resonance spectroscopy (MRS) is another non-invasive imaging technique that has the ability measure neurometabolites. It does this via proton magnetic resonance spectroscopy. Changes in NAA, choline, and Cr ratios demonstrated by MRS have been associated with individuals who have experienced a traumatic brain injury. In one particular study by Vagnozzi, it was shown that athletes reported resolution of post-concussive symptoms by post-injury day 3, despite continued MRS abnormalities. Further findings also suggest that complete metabolic recovery may be delayed if a second concussion occurs within a short time-interval from the first and that further abnormal metabolic changes may take place. This suggests that there are chronological differences in clinical recovery and metabolic recovery following a mild traumatic brain injury [33].

Small, et al. more recently has looked at PET scanning of brain tau protein in retired NFL players. Preliminary data showed that brain tau protein markers in all subcortical regions as well as the amygdala, were higher in retired NFL players than controls. There was a rather small sample size and lack of autopsy confirmation in regards to this small study, but this does show some potential for offering premorbid identification of neurodegeneration in athletes [34].

Earlier Diagnosis of CTE:

The only true way to diagnose CTE is post-mortem via an autopsy. Recent work by Maruyama and colleagues has been promising in the field of *in vivo* radiographic detection of tau inclusions. This group has developed a class of tau ligands specifically utilized for the visualization of diverse tau inclusions within the brains of

individuals afflicted with tauopathies, such as Alzheimer's Disease. These ligands are able to penetrate the blood-brain-barrier and have the capability of binding to and ultimately visualizing aggregations of intracellular tau protein. The group's *in vivo* imaging studies have demonstrated intensified signals in tau-rich regions of the brain [35]. Once such earlier methods of tau aggregate detection are further refined, the possibility of diagnosing CTE prior to its deleterious effects taking place on the individual may be possible. Clinicians will then have a more definitive diagnosis for which an adequate treatment plan can be formulated.

Animal Models of CTE:

A multitude of traumatic brain injury animal models have been created over the years, but no model has sought to replicate the spectrum of neurobehavioral changes seen in CTE until recently. Huang and colleagues have developed a hybrid animal model combining two of the more popular TBI models, in an effort to demonstrate neurobehavioral changes concurrent with CTE. Their closed-head injury model is unique in that it includes *un-anesthetized* mice as the subjects. Typical anesthetics used in TBI models have the ability to pose as a significant confounding factor, given some of their neuro-toxic and neuro-protective effects. The mice within this study were helmeted, with their heads free to move into a foam base after impact. The strategies implemented in this model strive to replicate as precisely as possible, the environment with which humans are subjected to prior to being afflicted with the untowardly effects of full-blown CTE. Some of the neurobehavioral changes seen in humans diagnosed with CTE were able to be replicated in mice with this novel model. In addition, a variety of neuropathological changes typically seen in CTE were demonstrated as well [36]. Further refinement of this new model will inevitably take place in the future, allowing researchers and clinicians to bridge the gap between the lab and clinical arena.

Conclusions

Chronic mild traumatic brain injury leading to encephalopathy is a serious condition, often overlooked because of the paucity of early dramatic symptoms and signs, as well as lack of findings on routine radiographic imaging. However, mTBI can be a disabling condition, leading to both emotional and physical abnormalities later on in an athlete's life. Routine neuroradiographic imaging generally does not show any significant findings; however, newer MRI-based techniques such as DTI, fMRI, and MRS have shown promise for earlier detection. Clinical presentation of CTE typically occurs in three stages. Once the third stage is reached, full blown Parkinsonism is often encountered. Our understanding today is that CTE likely results from progressive neuronal loss, and that once the cascades are started, the symptoms of mTBI continue to progress. This further highlights the paramount importance of sport-specific preventive strategies and early detection in our athletes.

Additional Information

Disclosures

Conflicts of interest: In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

References

1. Flannagan P, Bailes J: Neurological injury in athletes. *Contemp Neurosurg*. 1998, 20:1-7.
2. Center for Disease Control and Prevention: Heads up: Concussion in youth sports . Center for Disease Control and Prevention. 2009, Accessed: November 20, 2014: <http://www.cdc.gov/concussion/HeadsUp/youth.html>.
3. Powell JW, Barber-Foss KD: Traumatic brain injury in high school athletes . *JAMA*. 1999, 282:958-63.
4. Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD: Concussions among United States high school and collegiate athletes. *J Athl Train*. 2007, 42:495-503.
5. Rabadi MH, Jordan BD: The cumulative effect of repetitive concussion in sports . *Clin J Sport Med*. 2001, 11:194-8.
6. Cantu RC: Head injuries in sport. *Br J Sports Med*. 1996, 30:289-96.
7. McKee AC, Cantu RC, Nowinski CJ, Hedley-Whyte ET, Gavett BE, Budson AE, Santini VE, Lee HS, Kubilus CA, Stern RA: Chronic traumatic encephalopathy in athletes: Progressive tauopathy after repetitive head injury. *J Neuropathol Exp Neurol*. 2009, 68:709-35. [10.1097/NEN.0b013e3181a9d503](https://doi.org/10.1097/NEN.0b013e3181a9d503)
8. Webbe FM, Barth JT: Short-term and long-term outcome of athletic closed head injuries . *Clin Sports Med*. 2003, 22:577-92.
9. Macciocchi SN, Barth JT, Alves W, Rimel RW, Jane JA: Neuropsychological functioning and recovery after mild head injury in collegiate athletes. *Neurosurg*. 1996, 39:510-4.
10. Collins MW, Lovell MR, Iverson GL, Cantu RC, Maroon JC, Field M: Cumulative effects of concussion in high school athletes. *Neurosurg*. 2002, 51:1175-9.
11. Martland H: Punch drunk. *JAMA*. 1928, 91:1103-1107. [10.1001/jama.1928.02700150029009](https://doi.org/10.1001/jama.1928.02700150029009)
12. Millsbaugh JA: Dementia pugilistica. *US Nav Med Bull*. 1937, 35:297-303.

13. Courville CB: Punch drunk. Its pathogenesis and pathology on the basis of a verified case . *Bull Los Angel Neuro Soc.* 1962, 27:160-8.
14. Corsellis JA, Bruton CJ, Freeman-Browne D: The aftermath of boxing. *Psychol Med.* 1973, 3:270-303.
15. Brandenburg W, Hallervorden J: Dementia pugilistica with anatomical findings (article in German) . *Virchows Arch.* 1954, 325:680-709.
16. Maxwell WL, Domleo A, McColl G, Jafari SS, Graham DI: Post-acute alterations in the axonal cytoskeleton after traumatic axonal injury. *J Neurotrauma.* 2003, 20:151-68.
17. Maxwell WL, MacKinnon MA, Smith DH, McIntosh TK, Graham DI: Thalamic nuclei after human blunt head injury. *J Neuropathol Exp Neurol.* 2006, 65:478-88.
18. Omalu BI, DeKosky ST, Minster RL, Kamboh MI, Hamilton RL, Wecht CH: Chronic traumatic encephalopathy in a National Football League player. *Neurosurg.* 2005, 57:128-34.
19. Omalu BI, Fitzsimmons RP, Hammers J, Bailes J: Chronic traumatic encephalopathy in a professional American wrestler. *J Forensic Nurs.* 2010, 6:130-6. [10.1111/j.1939-3938.2010.01078.x](https://doi.org/10.1111/j.1939-3938.2010.01078.x)
20. Lakis N, Corona RJ, Toshkezi G, Chin LS: Chronic traumatic encephalopathy - neuropathology in athletes and war veterans. *Neurol Res.* 2013, 35:290-9. [10.1179/1743132813Y.0000000177](https://doi.org/10.1179/1743132813Y.0000000177)
21. Echemendia RJ, Julian LJ: Mild traumatic brain injury in sports: Neuropsychology's contribution to a developing field. *Neuropsychol Rev.* 2001, 11:69-88.
22. Jordan BD: Neurologic aspects of boxing. *Arch Neurol.* 1987, 44:453-9.
23. Stiller JW, Weinberger DR: Boxing and chronic brain damage. *Psychiatr Clin North Am.* 1985, 8:339-56.
24. Geddes JF, Vowles GH, Nicoll JA, Révész T: Neuronal cytoskeletal changes are an early consequence of repetitive head injury. *Acta Neuropathol.* 1999, 98:171-8.
25. Buée L, Hof PR, Bouras C, Delacourte A, Perl DP, Morrison JH, Fillit HM: Pathological alterations of the cerebral microvasculature in Alzheimer's disease and related dementing disorders. *Acta Neuropathol.* 1994, 87:469-80.
26. McKee AC, Gavett BE, Stern RA, Nowinski CJ, Cantu RC, Kowall NW, Perl DP, Hedley-Whyte ET, Price B, Sullivan C, Morin P, Lee HS, Kubilus CA, Daneshvar DH, Wulff M, Budson AE: TDP-43 proteinopathy and motor neuron disease in chronic traumatic encephalopathy. *J Neuropathol Exp Neurol.* 2010, 69:918-2. [10.1097/NEN.0b013e3181ee7d85](https://doi.org/10.1097/NEN.0b013e3181ee7d85)
27. Barmada SJ, Skibinski G, Korb E, Rao EJ, Wu JY, Finkbeiner S: Cytoplasmic mislocalization of TDP-43 is toxic to neurons and enhanced by a mutation associated with familial amyotrophic lateral sclerosis. *J Neurosci.* 2010, 30:639-49. [10.1523/JNEUROSCI.4988-09.2010](https://doi.org/10.1523/JNEUROSCI.4988-09.2010)
28. Zhang L, Heier LA, Zimmerman RD, Jordan B, Ulug AM: Diffusion anisotropy changes in the brains of professional boxers. *AJNR Am J Neuroradiol.* 2006, 27:2000-4.
29. Hagel B, Meeuwisse W: Risk compensation: a "side effect" of sport injury prevention? . *Clin J Sport Med.* 2004, 14:193-6.
30. Ptito A, Chen JK, Johnston KM: Contributions of functional magnetic resonance imaging (fMRI) to sport concussion evaluation. *NeuroRehabilitation.* 2007, 22:217-27.
31. Henry LC, Tremblay J, Tremblay S, Lee A, Brun C, Lepore N, Theoret H, Ellemberg D, Lassonde M: Acute and chronic changes in diffusivity measures after sports concussion. *J Neurotrauma.* 2011, 28:2049-59. [10.1089/neu.2011.1836](https://doi.org/10.1089/neu.2011.1836)
32. Maruta J, Lee SW, Jacobs EF, Ghajar J: A unified science of concussion . *Ann N Y Acad Sci.* 2010, 1208:58-66. [10.1111/j.1749-6632.2010.05695.x](https://doi.org/10.1111/j.1749-6632.2010.05695.x)
33. Pulsipher DT, Campbell RA, Thoma R, King JH: A critical review of neuroimaging applications in sports concussion. *Curr Sports Med Rep.* 2011, 10:14-20. [10.1249/JSR.0b013e31820711b8](https://doi.org/10.1249/JSR.0b013e31820711b8)
34. Small GW, Kepe V, Siddarth P, Ercoli LM, Merrill DA, Donoghue N, Bookheimer SY, Martinez J, Omalu B, Bailes J, Barrio JR: PET scanning of brain tau in retired national football league players: Preliminary findings. *Am J Geriatr Psychiatry.* 2013, 21:138-44. [10.1016/j.jagp.2012.11.019](https://doi.org/10.1016/j.jagp.2012.11.019)
35. Maruyama M, Shimada H, Suhara T, Shinotoh H, Ji B, Maeda J, Zhang MR, Trojanowski JQ, Lee VM, Ono M, Masamoto K, Takano H, Sahara N, Iwata N, Okamura N, Furumoto S, Kudo Y, Chang Q, Saido TC, Takashima A, Lewis J, Jang MK, Aoki I, Ito H, Higuchi M: Imaging of tau pathology in a tauopathy mouse model and in Alzheimer patients compared to normal controls. *Neuron.* 2013, 79:1094-108. [10.1016/j.neuron.2013.07.037](https://doi.org/10.1016/j.neuron.2013.07.037)
36. Petraglia AL, Plog BA, Dayawansa S, Chen M, Dashnaw ML, Czerniecka K, Walker CT, Viterise T, Hyrien O, Iliff JJ, Deane R, Nedergaard M, Huang JH: The spectrum of neurobehavioral sequelae after repetitive mild traumatic brain injury: a novel mouse model of chronic traumatic encephalopathy. *J Neurotrauma.* 2014, 31:1211-24. [10.1089/neu.2013.3255](https://doi.org/10.1089/neu.2013.3255)